2006

Response of structures to blast: a new criterion

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RESPONSE OF STRUCTURES TO BLAST: A NEW CRITERION

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DISTRIBUTED-ENERGY AND LUMPED-ENERGY EXPLOSIONS

A fuel-air explosion, for example one from a gasoline vapor and air mixture, is characterized by the circumstance that the explosive energy is initially distributed and released throughout a relatively large volume. This contrasts with an explosion from a material such as dynamite, where the energy release is initially concentrated into a relatively small volume.

Important aspects of distributed-energy explosions include (1) how these explosions compare and contrast with concentrated-energy explosions, particularly with regard to respective damage potentials and (2) what constitutes a valid index or criterion for damage potential. Reported here are the results of both theoretical and experimental studies made in these connections. Excellent correlation between theoretical considerations and experimental measurements has been obtained, largely through a new damage criterion for blast damage potential. This new proposed criterion appears to have substantial utility in the study both of distributed-energy and of concentrated-energy explosions.

CONVENTIONAL DAMAGE CRITERIA

A key aspect in the study of explosions is the criterion used as an index of their damage potential. Let us consider first the situation where a conventional and typical criterion for blast damage potential, the peak overpressure, is used. The scaling laws for explosions[1,2,3] state that the developed peak overpressure is a unique function of a "scaled" distance (see appendix).

This observation may be stated alternatively to the effect that the radial distance to which a specified peak overpressure extends, r_P, varies directly with the cube root of the explosive energy release, W. Then the area covered by a specified peak overpressure, A_P (or πr_P^2), becomes

$$A_P = \pi k^2 W^{2/3} \tag{1}$$

where k is the constant of proportionality for the distance relation.

Now in the situation where the explosive charge is divided into n equal fractional charges, the area covered by each of these fractional charges A_P', becomes

$$A_P' = \pi k^2 (W/n)^{2/3} \tag{2}$$

The total of n such areas is the area covered by the specified peak overpressure when the charge is distributed into n segments and there is negligible overlapping or mutual interference. The relationship between the total areas for the two situations is

$$\text{ratio } \frac{\text{area for distributed charge}}{\text{area for lumped charge}} = n\, A_P' \,/\, A_P = n^{1/3} \tag{3}$$

This relation states that the damage effectiveness of the distributed-energy explosion is increased over that of the lumped-energy explosion by the cube root of the number of segments into which the charge is divided.

Conclusions such as this have at times been used as arguments for the tactical use of distributed-charge weapons rather than lumped-charge ones. Note, however, that the relation cannot hold as the number of segments increases indefinitely. Then the computed area approaches infinity, whereas no finite amount of explosive can cover an infinite area. It is this very situation, however, that is approached by the molecular dispersion of a fuel-vapor–air explosion. It must therefore be concluded that the behavior of a distributed-charge explosion is somehow different from that of a lumped-charge, or else that the peak overpressure is not entirely suitable as a criterion for the blast damage potential of explosions, particularly those from distributed charges. This latter conclusion is one that is well recognized.

An alternative and possible improvement over peak overpressure as a criterion for blast damage potential has been suggested: the explosive impulse per unit area, or time integral of the overpressure. The scaling laws do not provide explicitly for a determination of the distance to which a given impulse extends. However, this may be determined indirectly as a function of the explosive energy release, by conventional methods outlined in the appendix. Results of such computations are shown in the form of a log-log plot in FIGURE 1. Here it can be seen that for a wide range of about three decades of explosive energy release, the distance to which a given impulse extends is directly proportional to the 0.60 power of the explosive energy release for side-on values, and to the 0.55 power for reflected values. For purposes of illustration, the side-on values are used,

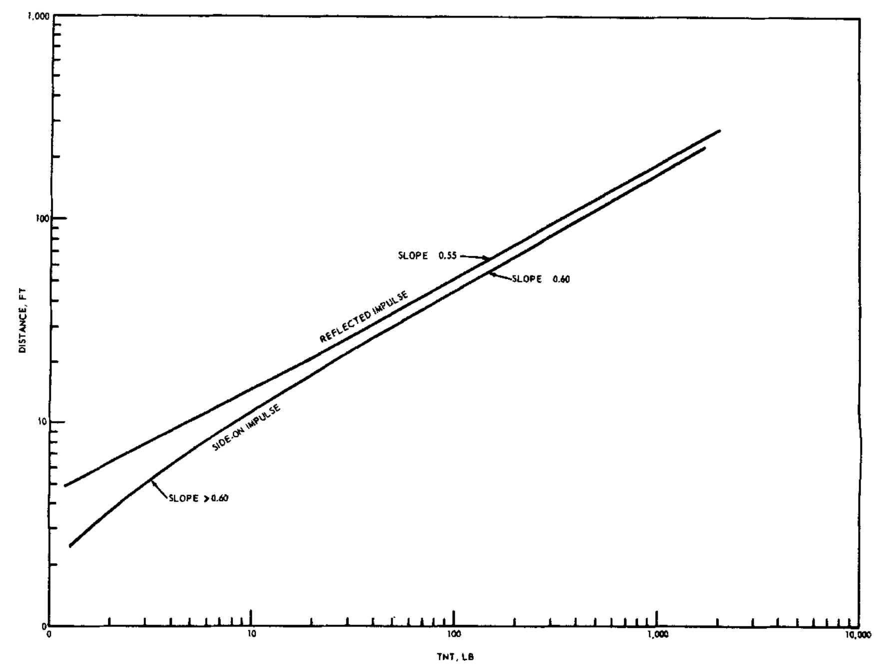

FIGURE 1. Distance to which a given impulse extends versus explosive yield.

and the area covered by a particular side-on impulse value, $A_{I,s}$ becomes proportional to $(W^{0.6})^2$, or

$$A_{I,s} = \pi k^2 W^{1.2} \tag{4}$$

where

W is the explosive energy release, and
k is the constant of proportionality for the distance relation.

For a charge divided into n equal segments, the area covered by each segment is $\pi k^2 (W/n)^{1.2}$, and that for n segments is

$$n\, A_{I,s}' = \pi k^2 W^{1.2}/n^{0.2} \tag{5}$$

The relationship between this area and that for the lumped charge is

$$\text{ratio}\ \frac{\text{area for distributed charge}}{\text{area for lumped charge}} = n^{-0.2} \tag{6}$$

This relation states that the blast damage effectiveness of the distributed charge is reduced from that of the lumped charge by the fifth root of the number of segments into which a charge is divided. It also indicates that in the limit of a molecularly dispersed fuel-vapor-air mixture, a negligible damage potential is reached. This is an erroneous conclusion, as every internal combustion engine with preignition knock testifies. Similar erroneous conclusions are reached if reflected impulse values are considered. Hence, it appears that impulse is not entirely suitable as a criterion for the blast damage potential of an explosion, particularly one from distributed charges. This situation also is well recognized.

New Criterion for Blast Damage Potential

Neither of the two blast damage criteria considered above—peak overpressure or impulse per unit area—appears to be applicable to the study of distributed-energy explosions, and certainly their conflicting conclusions about the effect of distributed charges cannot both be correct. Thus, in the study of distributed-energy explosions there is need for a realistic criterion for blast damage capability. It is of interest to note that this same need also exists for ordinary lumped-charge explosions, although this conclusion is reached through other considerations.

A detailed examination of the two conventional criteria for blast damage potential reveals that the peak overpressure criterion is deficient in that it predicts a damage capability that is the same both for very, very short disturbances and for sustained high pressures, provided only that the peak values are the same. Likewise, the impulse criterion is deficient in that it considers as damaging those small and actually undamaging overpressures that are applied over a long period of time.

To overcome these diverse difficulties, there is suggested the concept that the damage potential of any explosive blast lies in its ability to deliver a sustained pressure effect, but for some minimum time. A criterion of this type can conveniently be expressed in terms of a blast wave impulse deliverable within a critical time. As such, this criterion is intermediate between the two criteria discussed above and so escapes their mathematical difficulties at the limit of a highly distributed charge.

A consequence of the proposed criterion for blast damage potential is that there must also exist for each target some critical impulse above which the target is damaged if such impulse is received within a critical time, but below which there is no effect. This proposed criterion also carries within it the important consideration that a minimum overpressure is required in order for a blast wave to inflict damage to a given structure, this minimum being the ratio of the critical impulse to the critical time. It is possible to calculate these critical values from basic engineering data for simple structures. It may be noted also that the proposed criterion of a critical impulse within a critical time is consistent with deductions from related studies on impact sensitivity.[4]

Critical Time

The identification and selection of the critical time within which an impulse must be received by a target in order to have damage inflicted is essentially empirical. However, there are available some theoretical guidelines. Thus, for a simple system at rest but capable of harmonic motion, a maximum velocity and maximum amplitude of swing are given by an impulse of very short duration.

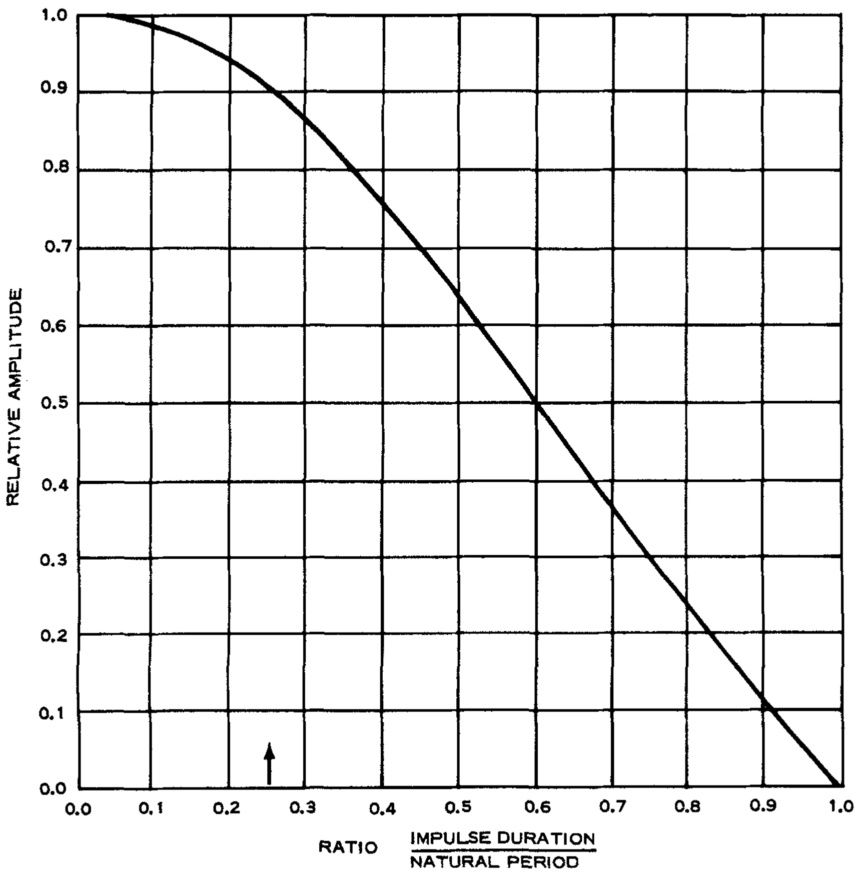

Figure 2. Relative amplitude of undamped harmonic motion versus duration of applied impulse.

Increasing the duration of the given impulse results in a decrease in achieved velocity and amplitude. However, this decrease is relatively small until the duration of the impulse becomes about one-quarter of the natural period of oscillation, when further increases give marked decreases in amplitude. These observations have been amply confirmed by analog computer studies[5] as illustrated in FIGURE 2. In addition, it may be noted that a simple harmonic oscillator travels from zero to maximum displacement in one-quarter of its natural period and that the enforced motion of a structural member leading to damage effects should not be greatly different.

On a basis of these considerations, it appears that a time equal to one-quarter of the natural period of oscillation should for any structural element represent a rough sort of cut-off time for impulse effectiveness. Representative calculations based on the determination of such natural periods are discussed in the following section.

In addition to structural deformations as a form of blast damage, there is also the situation where an object such as a truck or a body is physically displaced and hurled from its original position. The forces giving rise to such a hurling action must at least be sufficiently great to override the forces of gravity, and they are arbitrarily taken to be those forces which by acting for one second can produce the corresponding free-fall velocity. A time in the order of one second thus becomes the critical time for blast damage received by this hurling mechanism.

To summarize, the critical times for explosive blast damage are arbitrarily but reasonably taken as one-quarter of the natural period for structures and structural members, and one second for destructive hurling away for nonattached objects.

Critical Impulse

Structural damage inflicted by explosive blast is the result of an impulsive load that exceeds the resistance of a material. In ordinary impulsive loading, a stress wave moves through the material such that

$$\sigma = \rho C V, \tag{7}$$

where

- σ is the stress,
- ρ is the density,
- C is the velocity of sound in the material, and
- V is the relative particle velocity associated with the stress wave (the product ρC is known as the "acoustic impedance")

For the limiting situation where the stresses developed are equal to the dynamic yield strength, there also is a limiting or critical particle velocity, V_c, which if exceeded causes permanent displacement within the material.

Experimental values for this critical particle velocity are available[6] for the tensile failure of some of the common metals. For other materials, the critical particle velocity can in principle be found from the dynamic yield strength when such dynamic yield values are known (they are appreciably greater than the conventional static values). However, blast produced failures are seldom ones in simple tension. Hence, the critical particle velocity applicable in the disruption of a target by blast is not so simply described, but it should be at least closely related to the critical particle velocity for failure in simple tension. For purposes here, these two critical particle velocities will be considered as being identical.

For blast damage, the critical particle velocity is actually a differential velocity referenced to a part of the system at rest. Consider, for example, a structural system where a skin is stretched between two rigid support members. When an impulsive load is applied, the inertia of the support members keeps them from moving significantly, while the thinner skin is accelerated to a velocity that may exceed the critical velocity, in which case tearing of the skin results. Similar considerations apply in systems that cantilever out from a massive inertial reference system, such as the empennage or the wing of an aircraft cantilevered out from the fuselage.

The critical impulse per unit area associated with the critical velocity is given by elementary considerations[6] as

$$I_c = \rho\delta V_c \tag{8}$$

where

ρ is the density of the target material,
δ is the thickness of the material, and
V_c is the critical velocity.

The critical impulse may also be expressed in terms of the dynamic yield strength for the material by combining the above relations to give

$$I_c = \delta\sigma_y/C \tag{9}$$

where

C is the velocity of sound in the material, and
σy is the dynamic yield strength.

The velocity of sound, C, can be replaced by its equivalent

$$C = \sqrt{E/\rho}$$

where

E is the modulus of elasticity

and this gives a third form for the expression for critical impulse

$$I_c = (\rho/E)^{1/2}\delta\sigma_y \tag{10}$$

These three forms of the expression for critical impulse are all expressed in coherent units and are all equivalent. The first of these would appeal to those who have worked with impulsive loads and shock waves in metals, but the others may on occasion be preferred since they contain items directly related to the ordinary strength characteristics of a material.

The above expressions apply as part of the criterion for blast damage when the damage occurs by deformations of a structure or a structural member. For the important situation where a target is damaged by hurling it bodily from its original position, the critical impulse is arbitrarily taken to be that which could cause the entire object to reach free-fall velocity in one second. This is convenient mathematically, and also is in accord with the observation that the corresponding fall of about 16 feet is ordinarily very damaging to most targets of interest.

Representative Calculations

Values for the blast damage criterion, critical impulse within a critical time, were computed both for a parked aircraft and for a light industrial building. For the aircraft, three types of damage were considered: (1) tearing the skin, (2) breaking off a wing section, and (3) physical displacement by hurling the entire plane.

Aircraft Skin Failure

For damage by the mechanism of tearing the skin, the critical time is taken from a computed value for the resonant frequency of this structural member. The skin was assumed to be of 1/16-inch-thick aluminum, clamped to stringers on 8-inch separation. For clamped panels of infinite length, the resonant frequency, f, is given by the relation[7]

$$f = 217{,}600 \times 0.985 \times \delta/b^2 \tag{11}$$

where the factor 217,600 pertains to this type of structure, and the factor 0.985 is for the type of metal.

Here

δ is the skin thickness in inches, and
b the distance of spacing in inches.

Thus,

$$f = 217{,}600 \times 0.985 \times (1/16)\ (8)^2 = 212 \text{ cps} \tag{12}$$

This resonant frequency corresponds to a natural period of vibration of 1,000/212 = 4.70 milliseconds (ms), and to a critical time of 4.70/4 = 1.2 ms.

The critical impulse required for tearing the skin is computed in any one of three separate ways, depending on the primary data available. Data on the aluminum skin, as obtained from various sources[6,7,8] are as follows.

δ	(thickness)	=	1/16 inch = 0.0052 feet
ρ	(density)	=	2.7 g/cm^3 = 2.7 × 62.4/32.2 = 5.22 slugs/ft^3
C	(speed of sound)	=	16,470 fps
V_c	(critical velocity)	=	240 fps
σ_y	(dynamic yield strength)	=	140,000 psi = 2.02 × 10^7 psf
E	(elastic modulus)	=	11 × 10^6 psi = 1.58 × 10^9 psf

1. Critical impulse from critical velocity:

$$I_c = \rho\delta V_c = 5.22 \times 0.0052 \times 240 = 6.5 \text{ psf-sec} = 45 \text{ psi-ms} \tag{13}$$

2. Critical impulse from dynamic yield strength and speed of sound:

$$I_c = \delta\sigma_y/C = 0.0052 \times 2.02 \times 10^7/16{,}470 = 6.4 \text{ psf-sec} = 44 \text{ psi-ms} \tag{14}$$

3. Critical impulse from elastic modulus and dynamic yield strength:

$$I_c = (\rho/E)^{1/2}\,\delta\sigma_y = (5.22/1.58 \times 10^9)^{1/2} \times 0.0052 \times 2.02 \times 10^7 = 6.0 \text{ psf-sec} = 42 \text{ psi-ms} \tag{15}$$

Differences in the calculated results, which in this instance are minor, are caused by disparities in the original data.

A diagram illustrating skin rupture as caused by a blast impulse that exceeds the critical impulse for the skin within the critical time is shown schematically in FIGURE 3. FIGURE 4 shows a typical skin failure of this type.

The computed minimum overpressure for this damage becomes 43/1.2 = 36 psi, which must persist for at least as long as 1.2 ms in order to provide the necessary minimum impulse.

Aircraft Wing Break-Off

In calculations of values for tearing off sections such as the empennage or the wing of an aircraft, the first problem is that of determining the resonant period

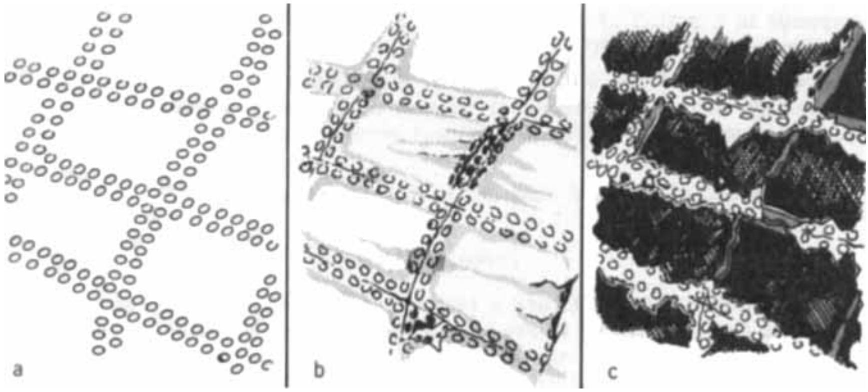

FIGURE 3. Rupture of structural skin panel. Computed critical impulse, 43 psi-ms; computed critical time, 1.2 ms.

FIGURE 4. Typical aircraft skin failures.

of the structure. This in principle can be done through use of conventional formulas for cantilevered beams,[7] but complications such as the stiffening action of various braces make such computations unreliable. Hence, experimentally determined values should be used whenever such data are available. In a generic type aircraft[9] of reasonably small dimensions, the resonant frequency for the wing and empennage sections is known to be approximately 5 cps. This corresponds to a period of 200 ms and gives a critical time represented by the quarter period of about 50 ms.

For estimate of the critical impulse, the major resistance of the wing or empennage section is assumed to be that of two skin sections, ignoring the support members. This gives the critical impulse value for wing break-off as $2 \times 43 = 86$ psi-ms.

A schematic of a typical wing break-off is shown in FIGURE 5.

Tumbled Aircraft

The critical value for hurling a total aircraft is based on the assumption of achieving free-fall velocity at one second. On this basis, the critical time is taken arbitrarily as one second, or 1,000 ms. The critical impulse thus becomes the product of the mass and the free-fall velocity of 32.2 fps.

The total mass of the object in pounds is converted to a mass in slugs by dividing by 32.2. Then multiplication by the assigned free-fall velocity gives the total impulse, in pounds force-seconds, that numerically equals the mass in pounds. Dividing by the area provides, with proper conversion factors, a specific impulse in psi-ms.

The typical total mass of a generic fighter aircraft[9] may be taken as 15,000 pounds mass, corresponding to a total critical impulse of 15,000 pounds force-seconds. We chose values for three areas for the aircraft.

Maximum area with both wings and fuselage seen, 500 ft.^{2} The critical impulse is then

$$I_{cT} = (15{,}000 \times 1{,}000)/(500 \times 144) = 208 \text{ psi-ms} \quad (16)$$

Side-on area, fuselage only, 200 ft^2

$$I_{cF} = (15{,}000 \times 1{,}000)/(200 \times 144) = 520 \text{ psi-ms} \quad (17)$$

Minimum area, directly head-on, 50 ft^2

$$I_{cH} = (15{,}000 \times 1{,}000)/(50 \times 144) = 2{,}080 \text{ psi-ms} \quad (18)$$

The value chosen for the actual target would probably be a weighted average of these attack situations and would be in the range of 500 to 1,000 psi-ms.

An aircraft hurled bodily from its position is indicated schematically in FIGURE 6. The resulting damage, however, comes about largely as a result of its subsequent collision, either with buildings, other aircraft, or the ground.

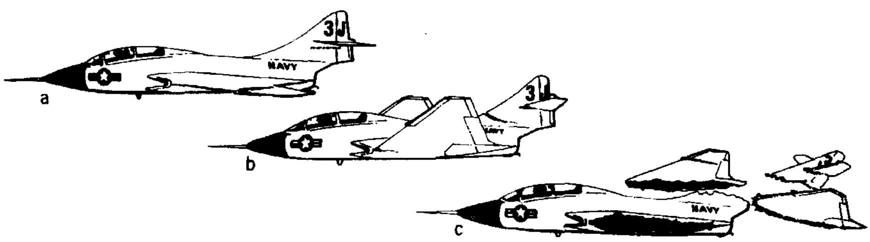

FIGURE 5. Aircraft wing break-off. Computed critical impulse, 86 psi-ms; computed critical time, 50 ms.

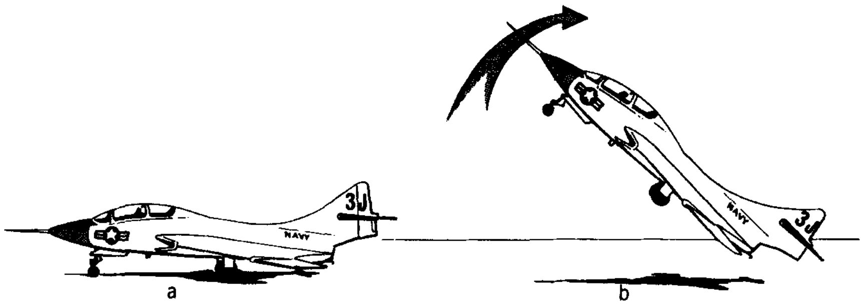

FIGURE 6. Aircraft tumbles when ordinary forces of gravity are overridden. Assumed critical time, 1,000 ms; weighted average critical impulse, 500–1,000 psi-ms.

Light Industrial Building

A structure of interest is a light industrial building similar to one used at the Nevada test site in tests for the effects of nuclear weapons (FIGURE 7). This rigid steel frame building is about 60 feet long and 15 feet high, with the walls divided into panels each 5 feet high and 20 feet long. The skin is of aluminum about 0.040 inch thick, with vertical ribs folded out of the material every 18 inches. In such a building there are many different resonant frequencies and many critical impulses; attention here is limited to possible skin rupture.

The skin of the building is treated as a panel of 0.040-inch-thick aluminum, 18 inches by 5 feet, supported along the four edges. The resonant frequency is given by the relation[7]

$$f = 225{,}600 \times 0.985 \times \delta/b^2 = 225{,}600 \times 0.985 \times 0.040/(18)^2 = 27.4 \text{ cps} \quad (19)$$

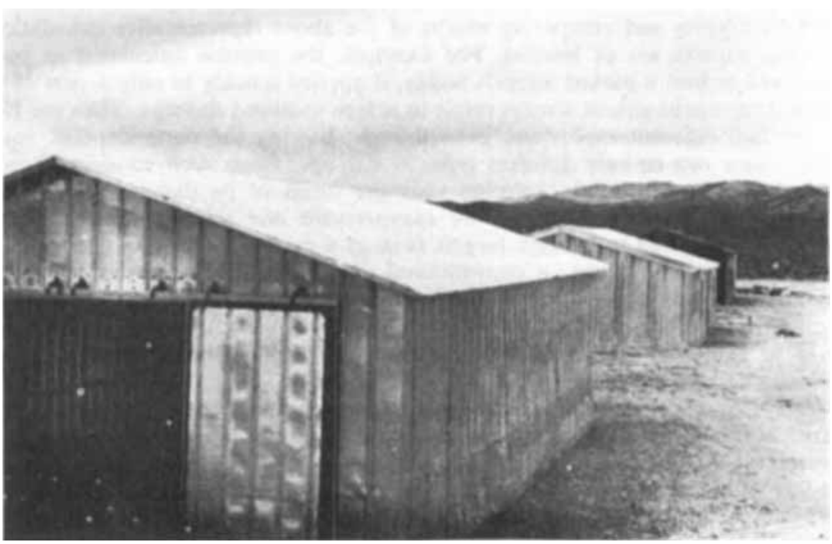

FIGURE 7. Typical light industrial building. Computed critical impulse for tearing the skin, 35 psi-ms; computed critical time, 9 ms.

where

δ is the skin thickness, in inches, and
b is the minor dimension, in inches.

The constant 225,600 applies to a system with the specified ratio of length to width, and the constant 0.985 corrects for aluminum. This resonant frequency represents a critical time of $1{,}000/(27.4 \times 4) = 9.1$ ms.

The critical impulse for a panel of this thickness becomes

$$I_c = 5.22 \times 0.040/12 \times 240 = 35 \text{ psi-ms} \tag{20}$$

where 5.22 is the density, and 240 is the critical velocity for aluminum.

A summary of the calculations is given in TABLE 1.

TABLE 1

CALCULATED VALUES OF CRITICAL TIME, CRITICAL IMPULSE, AND MINIMUM MEAN OVERPRESSURE FOR VARIOUS TYPES OF DAMAGE

	Critical time (ms)	Critical impulse (psi-ms)	Minimum mean overpressure (psi)
Tearing skin of aircraft	1.2	43	36
Breaking off aircraft wing	50	86	17
Hurling aircraft bodily:			
maximum area effective	1,000	208	0.2
side-on fuselage area	1,000	520	0.5
minimum area	1,000	2,080	2.0
weighted average	1,000	500–1,000	0.5–1.0
Light industrial building (skin ruptured)	9	35	4

RESULTS

In analyzing and comparing results of the above representative calculations, several aspects are of interest. For example, the impulse calculated as being required to hurl a parked aircraft bodily, if applied quickly to only a part of the structure, would almost always result in severe localized damage. Thus the blast from two different explosions, even though showing the same impulse, might well cause two entirely different types of damage. From such considerations, it develops that a nuclear explosion near the limits of its damage effectiveness with a widespread region of blast overpressure and relatively long duration might be expected to damage targets such as a parked aircraft by the tumbling mechanism. In contrast, a conventional explosion with a shorter range and relatively short duration might well be expected to cause damage more by the mechanism of severe localized stresses (FIGURE 8). Localized damage of such limited extent would not be expected from a distributed-energy explosion even though with the same energy release.

Another item with the new proposed damage criterion is that the ratio of critical impulse to critical time represents a minimum mean overpressure to be exceeded if damage is to occur. From this viewpoint, an overpressure of about $1{,}000/1{,}000 = 1.0$ psi (the exact value depends on aircraft orientation) and sustained for about one second, might be expected to damage a parked aircraft by a hurling or tumbling mechanism. For tearing the skin, however, a minimum mean overpressure of $43/1.2 = 36$ psi is indicated, but for the very short time

FIGURE 8. Highly localized damage by blast from a lumped-charge explosion.

of 1.2 ms. The predicted values of minimum mean overpressures for damage appear in these instances to be reasonably in accord with experimental observations.

Consider next the computations for the light industrial building. Here a minimum mean overpressure of $35/9 = 3.9$ psi (for at least 9 ms) is indicated as being required if rupture of the skin is to occur. Experimental results[2] for a nuclear blast of presumably long duration show that a peak side-on overpressure of 3.1 psi does not rupture the skin on the roof of such a structure exposed to this overpressure during a test (FIGURE 9). This is a gratifying agreement with prediction.

In the same blast situation, however, the face of the structure toward the

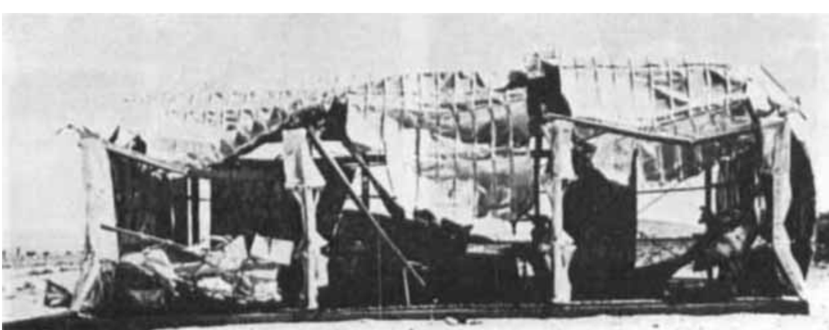

FIGURE 9. Widespread damage to light industrial building by blast from a nuclear explosion.

explosion is completely ruptured and torn away. But in this instance, the front face experiences an actual overpressure (in a Mach stem) that is the reflected overpressure rather than the side-on. This maximum reflected overpressure is calculated[3] to be about 6.7 psi. Such a reflected overpressure exceeds the predicted minimum of 3.9 psi, and so if maintained sufficiently long, it should completely disrupt the skin. This actually occurred, which again is in gratifying agreement with prediction. It should be noted, however, that the calculations of both minimum time and minimum impulse as made above and on which these comparisons are based, are sensitive to the thickness of the skin involved. This observation may be stated alternatively in the form that the blast resistance of a structure depends very much on the strength of its component elements.

These examples are concerned primarily with situations where characteristics of the explosion are known. For distributed-charge explosions, however, the situation may be less simple, for here the overpressure-time-distance relation is an involved one and depends among other things on the geometry of the explosion. This is illustrated in FIGURE 10, which shows successive frames of a high-speed motion picture of a planar explosion. It is evident that the explosion

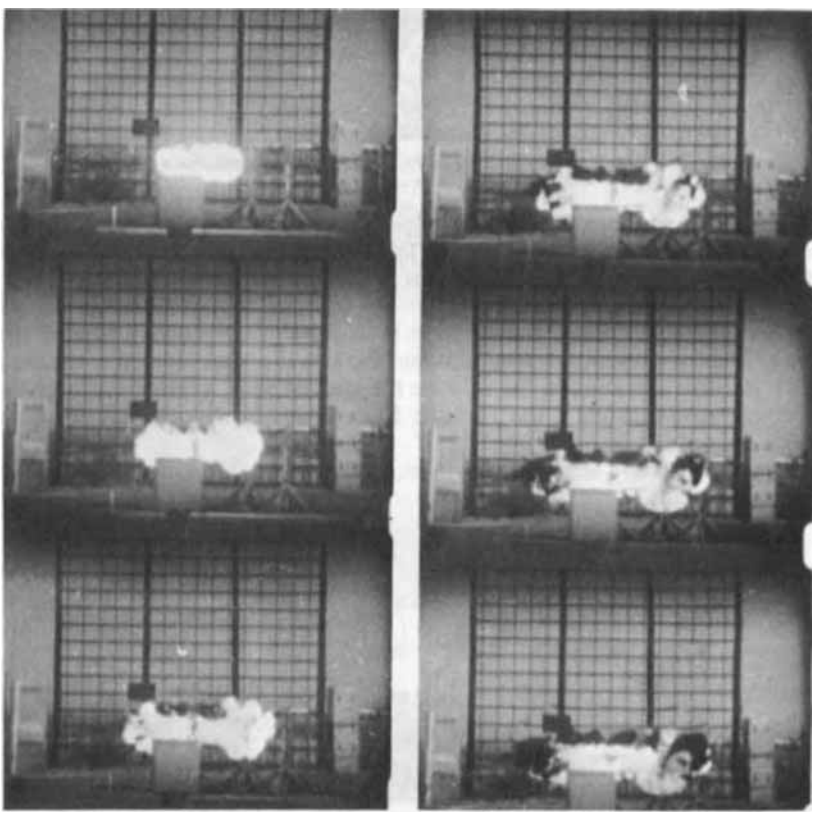

FIGURE 10. Unsymmetrical blast wave from a distributed-charge planar explosion. Successive exposures at intervals of about 0.35 ms; apparent grid spacing is about one foot.

products are moving far more rapidly in a direction normal to the plane of the explosion than in other directions; hence, the blast is more severe in this direction. A complete theoretical analysis of this phenomenon has not as yet been made, so that experimental data are required in order to assess the associated damage potential. Furthermore, to obtain meaningful data in such circumstances, it seems necessary to utilize both electrical (electronic) and photographic methods. From such, and using the concept of critical impulse within a critical time, the damage potential may readily be found. With regard to these items, it is of interest to note that at distances only moderately removed from a distributed explosion, the peak overpressure contours rapidly approach the spherical. In this situation the explosion behaves essentially as a lumped-charge one, and its damage potential may be estimated from conventional values for lumped charges. As a rough approximation, at distances some 5 to 10 times its longest dimension, a distributed charge shows lumped-charge behavior.

Conclusions

Ideally in predicting blast damage results, in establishing a test program for blast parameters, or in assessing blast damage effectiveness, the complete dynamic response of the target, the complete aerodynamic characteristics of the target in its environment, and the exact pressure, time, and position characteristics of the blast wave are required. In actual practice, however, it is exceedingly difficult to obtain all of these items with sufficient accuracy to make detailed computation and analysis worthwhile.

A new proposed criterion, critical impulse in a critical time, does take into account some of the principal effects that predominate in the equations of motion of a target subjected to an impulsive load. Thus, this is an approach to an absolute criterion for damage susceptibility which is based on the fundamental characteristics of the target: its material, its material behavior, its mode of construction, and the related modes of vibration.

When this criterion for damage susceptibility is applied, the damage potential of an explosive blast for any specified target is readily obtained. This is not a simple function of peak overpressure alone, nor of impulse alone, but is a combination of overpressure, decay characteristics of the blast wave, and the dynamic response of the target structure. It should be emphasized, however, that such a damage potential should be regarded as applicable only to a general situation and should not be considered as replacing a detailed analysis that can be applied to a specific target in a specific encounter situation.

This new index of damage potential is related to the conventional peak overpressure index in that the new criterion contains within it an estimate of the minimum overpressure required for damage to a specified target. Examination of such minimum overpressures reveals that a given overpressure, if generated in a large explosion, has a greater damage potential than if generated in a small one—an item of possible concern when the hazards of stored explosives are considered.

A further application for this new criterion for blast damage potential lies in an inverse situation where it is desired to provide for maximum resistance to blast. Thus, for a parked aircraft, simple precautions such as standard tie-downs to prevent tumbling are helpful in providing resistance to large explosions. For structures, it is indicated that tight, well-knit structural elements with high natural frequency of vibration are helpful in that they show a short critical time.

More important perhaps is the fact that adequate strength is required in all elements of a structure if it is to withstand explosive blast.

Appendix

The scaling laws for explosions are based on the principle of geometric similarity and on the observation that explosive energy dispersal in a uniform atmosphere is a volume effect proceeding equally in three dimensions. Then the distances for corresponding effects, for example the same overpressure ratio, become proportional to the cube root of the explosive yield. This leads to a definition of scaled distance as

$$(\text{scaled distance}) = (\text{actual distance})/(\text{yield factor})$$

where

$$(\text{yield factor}) = (\text{explosive yield})^{1/3}$$

for different explosions in the same atmosphere. In this situation, specifying an overpressure also specifies the scaled distance. The radial distance to this specified overpressure, r_P, becomes

$$r_P \, \alpha \, W^{1/3} \tag{21}$$

where W is the explosive yield, and the required proportionality constant becomes the above-defined scaled distance. This proportionality is the basis for Equation 1.

For consideration of the distances that give the same impulse effects, it is convenient also to introduce a paralled concept of scaled time, as

$$(\text{scaled time} = (\text{actual time})/(\text{yield factor})$$

Then from the definition of impulse per unit area as the time integral of the overpressure, the positive impulse per unit area for the explosive blast becomes

$$\left(\begin{matrix}(\text{Impulse})\\ \text{per unit area}\end{matrix}\right) =$$

$$(\text{peak overpressure}) \times (\text{decay factor}) \times (\text{scaled duration}) \times (\text{yield factor})$$

The decay factor of this relation accounts for the quasi-exponential decay of the blast and is a function of scaled distance. The required calculations proceed by specifying a positive impulse per unit area, followed by selecting several scaled distances of interest. Then for each scaled distance, the peak overpressure, the decay factor, and the scaled duration are obtained for the corresponding reference explosion. From these, the yield factor is computed by the above relation, and then both explosive yield and actual distance to the specified impulse value are readily found.

For purposes here, the values selected were those for a spherical charge of TNT explosive.[3] For side-on impulse calculations, peak side-on overpressures are found directly in the tables. For the reflected impulse, it was assumed that the side-on impulse is augmented during the reflection by a factor equal to one-half the reflection coefficient for the peak side-on overpressure.

The distances corresponding to a specified impulse were thus computed as a function of explosive energy release and plotted to log-log coordinates in FIGURE 1. A nearly straight line relationship is indicated. The corresponding empirical algebraic relation for the distance to which a specified positive side-on impulse per unit area, $r_{I,s}$, becomes, closely,

$$r_{I,s} \, \alpha \, W^{0.6} \tag{22}$$

Similarly, for reflected impulse

$$r_{I,R} \alpha W^{0.55} \tag{23}$$

The first of these proportionalities is the basis for Equation 4. Identical proportionalities, but requiring a different constant of proportionality, are obtained if other (but constant) values of impulse are selected.

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